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Abstract: Dark Matter and Double Beta Decay experiments require extremely low radioactivity within the detector materials. For this purpose, the University of California, Los Angeles and Hamamatsu Photonics have developed the QUartz Photon Intensifying Detector (QUPID), an ultra-low background photodetector based on the Hybrid Avalanche Photo Diode (HAPD) and entirely made of ultraclean synthetic fused silica. In this work we present the basic concept of the QUPID and the testing measurements on QUPIDs from the first production line. Screening of radioactivity at the Gator facility in the Laboratori Nazionali del Gran Sasso has shown that the QUPIDs safely fulfill the low radioactive contamination requirements for the next generation zero background experiments set by Monte Carlo simulations. The quantum efficiency of the QUPID at room temperature is $> 30\%$ at the xenon scintillation wavelength. At low temperatures, the QUPID shows a leakage current less than 1 nA and a global gain of 10^5 . *In these conditions, the photocathode and the anode show $> 95\%$ linearity up to 1 μ A for the cathode and 3 mA for the anode. $T_{1.8} = 1.8 \pm 0.1$ ns rise time, $T_{2.5} = 2.5 \pm 0.2$ ns fall time, $\tau = 4.20 \pm 0.05$ ns pulse width, and 160 ± 30 ps transittimespread. The QUPID*

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Characterization of the QUartz Photon Intensifying Detector (QUPID) for use in Noble Liquid Detectors

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Dark Matter and Double Beta Decay experiments require extremely low radioactivity within the detector materials. For this purpose, the University of California, Los Angeles and Hamamatsu Photonics have developed the QUartz Photon Intensifying Detector (QUPID), an ultra-low background photodetector based on the Hybrid Avalanche Photo Diode (HAPD) and entirely made of ultraclean synthetic fused silica. In this work we present the basic concept of the QUPID and the testing measurements on QUPIDs from the first production line.

Screening of radioactivity at the Gator facility in the Laboratori Nazionali del Gran Sasso has shown that the QUPIDs safely fulfill the low radioactive contamination requirements for the next generation zero background experiments set by Monte Carlo simulations.

The quantum efficiency of the QUPID at room temperature is $> 30\%$ at the xenon scintillation wavelength. At low temperatures, the QUPID shows a leakage current less than 1 nA and a global gain of 10^5 . In these conditions, the photocathode and the anode show $> 95\%$ linearity up to 1 μ A for the cathode and 3 mA for the anode. The photocathode and collection efficiency are uniform to 80% over the entire surface. In parallel with single photon counting capabilities, the QUPIDs have a good timing response: 1.8 ± 0.1 ns rise time, 2.5 ± 0.2 ns fall time, 4.20 ± 0.05 ns pulse width, and 160 ± 30 ps transit time spread.

The QUPIDs have also been tested in a liquid xenon environment, and scintillation light from ^{57}Co and ^{210}Po radioactive sources were observed.

Keywords: Dark matter; Double beta decay; Photomultiplier tubes; QUPID; Liquid xenon

1. INTRODUCTION

There is overwhelming indirect evidence that Dark Matter (DM) accounts for $\sim 25\%$ of the mass-energy of the universe. One of the most accredited theories predicts that Weakly Interacting Massive Particles (WIMPs) constitute the dark matter halos that permeate galaxies [1]. WIMPs are expected to undergo elastic collisions with noble liquid nuclei producing low energy deposits [2]. Some of the noble liquid experiments searching for WIMP interactions are XENON, ZEPLIN, LUX and XMASS [3–7] employing liquid xenon, and WARP, DEAP/CLEAN and DARKSIDE, using liquid argon [8–10].

Natural xenon contains the isotope ^{136}Xe , which is predicted to undergo double beta decay, normally accompanied by the production of two neutrinos ($2\nu\beta\beta$). The detection of two back-to-back electrons – or equivalently a peak in the energy spectrum at 2.458 MeV – would represent the unequivocal signature of neutrinoless dou-

ble beta decay ($0\nu\beta\beta$) proving that the neutrino is its own antiparticle (a Majorana particle) [11, 12]. Experiments using ^{136}Xe such as EXO, NEXT, and KamLAND-Zen [13–16] are underway.

Presently, the most sensitive dark matter detector using noble liquids has an effective target mass on the order of 100 kg with an expected background rate of $\sim 10^{-2}$ events/kg/day/keV¹ in the region of interest [17]. Next generation detectors, with target mass > 1 ton, will require a background rate $< 10^{-4}$ events/kg/day/keV to reach desired sensitivities. In order to decrease the background down to this quantity, several efforts are underway [18, 19]. Of particular importance is the radioactive contamination coming from the employed photodetectors, as they are the experimental components closest to the target material. Moreover, in present experiments a majority of the background rate originates from the conventional photomultiplier tubes (PMTs). A new photodetector, the QUartz Photon Intensifying Detector, or QUPID, has been invented as an ideal replacement

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¹ keVee and keVr are used to distinguish between electron recoil and nuclear recoil interactions. Throughout this paper, we will use keV in place of keVee.

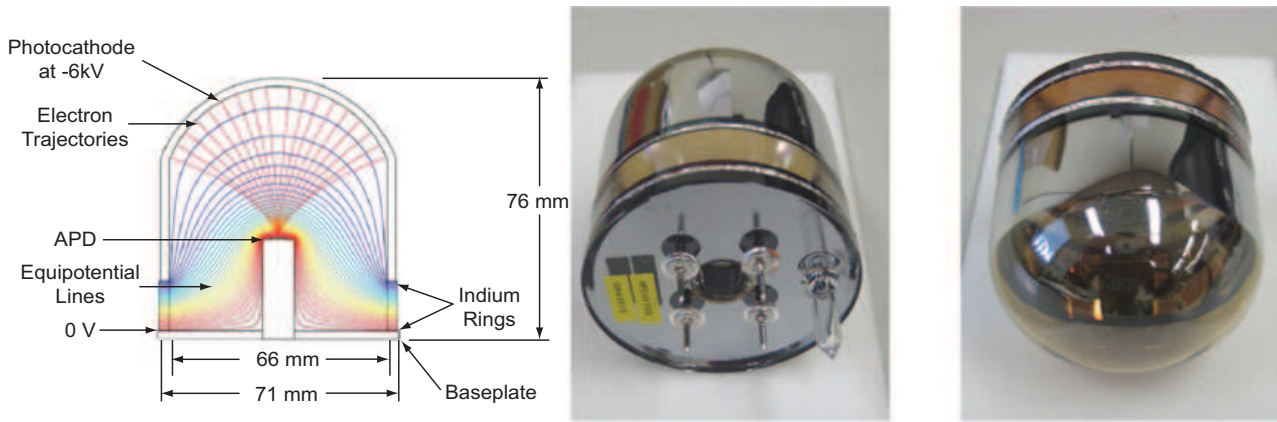


FIG. 1: On the *left* is a drawing of the QUPID showing the electric field and the electrons trajectory simulations. It can be seen that the photoelectrons are focused onto the APD. On the *center* and *right*, back and front views of the QUPID. Two indium rings, one used to provide -6 kV to the photocathode and the other for grounding, can be seen. The same rings hold the quartz cylinder, quartz ring, and baseplate together. On the baseplate, one can see four pins (two of them are connected to the APD cathode and anode, while the other two are used only during production). The glass pipe is used for pumping a vacuum during production.

for conventional PMTs² by the University of California, Los Angeles (UCLA) and Hamamatsu Photonics. In this work, we present the development and tests performed on a set of seven QUPIDs from an early production line. An explanation of the essential requirements that must be satisfied for dark matter and double beta decay detection, and the general QUPID concept are presented in Sec. 2 and 3 respectively. In Sec. 4 we discuss the radioactive screening of the QUPID at the Gator screening facility at the Laboratori Nazionali del Gran Sasso (LNGS) in Italy, performed by the University of Zurich group.

In Sec. 5 we examine the cathode performances and those of the anode in Sec. 6. Sec. 7 is devoted to single photon counting and time response tests, while in Sec. 8 we show the operation of the QUPID in liquid xenon³. In the last section, Sec. 9, we present a summary of the main achievements, asserting that the QUPIDs represent the most appropriate solution for the next generation of low background detectors.

2. PHOTODETECTOR REQUIREMENTS

The photodetectors which will be employed in the next generation experiments must meet the following requirements in order to improve the performance both by reducing the background contamination and increasing sensitivity:

- *intrinsic radioactivity* significantly lower than the current generation PMTs;
- *Quantum efficiency* $> 30\%$ to maximize the number of photoelectrons from a given energy deposit;
- high *gain* $> 10^5$ so that single photoelectrons can be clearly detected above the noise level;
- good *timing* performances with a pulse width < 10 ns, to provide accurate time information.
- good *collection efficiency* and *uniformity* along the photodetector surface;
- a large dynamic range with superior *linearity*, for precise measurement of energy depositions in the region of interest: from a few keV for dark matter searches to several MeV for neutrinoless double beta decay;

In the following sections we describe in some detail the tests performed proving the capability for the QUPID to satisfy these requirements.

3. CONCEPT

The QUPID is based on the Hybrid Avalanche Photodiode (HAPD). In HAPDs, photons hit the photocathode surface causing the emission of photoelectrons, which are accelerated onto an APD due to a high potential difference (several kV) between the photocathode and the APD. The kinetic energy of the electrons creates hundreds of electron-hole pairs within the APD. The electrons and holes are then separated and accelerated, because of the high bias voltage on the APD, undergoing an avalanche effect [20–22].

² US Patent Pending, Application No. 20100102408, M. Suyama, A. Fukasawa, K. Arisaka, H. Wang

³ Although a modified version of the QUPID optimized for operating in liquid argon is in development, in this work we will concentrate on the QUPID for liquid xenon.

Contaminant	Activity (mBq/QUPID)	Events/year in Fiducial Cut, Target Mass (after fiducial cut), Energy [2-18] keV		
		0 cm, 2.3 ton	5 cm, 1.6 ton	10 cm, 1.1 ton
^{238}U	< 17.3	< 560	< 0.5	0
^{226}Ra	0.3 ± 0.1	23	0.14	0.01
^{232}Th	0.4 ± 0.2	35	0.24	0.02
^{40}K	5.5 ± 0.6	55	0.32	0.02
^{60}Co	< 0.18	< 4.9	< 0.21	< 0.02
Total	< 23.7	< 678	< 1.41	< 0.07

TABLE I: First column: Contaminants present in the QUPID divided into the active chains. Second column: Measured intrinsic radioactivity of the QUPIDs. Remaining columns: Radioactive background from the QUPID in a ton-scale detector for different fiducial volume cuts in the 2-18 keV energy range. The relatively high contamination arising from ^{238}U , of about 17 mBq per QUPID, does not affect the region of interest as γ -rays from this chain do not penetrate deeply inside the liquid xenon. It can be easily cut out, down to zero events per year, by increasing the fiducial cut to 10 cm from each side.

On the left of Fig. 1, a drawing of the QUPID is presented, showing a simulation of the electric field equipotential lines and of the photoelectron trajectories from the photocathode onto the APD. Fig. 1 center shows the QUPID seen from the baseplate, and on the right from the hemispherical photocathode.

The QUPID is made of a cylindrical quartz tube with a hemispherical photocathode window, a baseplate, and an intermediate quartz ring. The quartz cylinder, ring, and baseplate are bonded together using indium (see Fig. 1 center and right). The outer diameter of the cylinder is 71 mm, with the hemispherical photocathode window having a radius of 37 mm. The photocathode has an effective diameter of 64 mm (for vertical incident photons). The inner part of the cylinder is coated with aluminum and the hemispherical cap is coated with a photocathode material. The baseplate on the opposite end supports a solid cylindrical quartz pillar with a 3 mm APD at the top. The APD (with 11 pF of capacitance) has been specifically developed and manufactured by Hamamatsu Photonics for use in the QUPIDs.

A negative high voltage, up to -6 kV, is applied to the photocathode through the indium sealing ring, while ground level is maintained on the baseplate and APD from the second indium ring. As in common HAPDs, the high potential difference creates an electric field which focuses the photoelectrons ejected from the photocathode onto the APD. The QUPID design has been optimized such that the photoelectron focusing is independent of the voltage applied to the photocathode.

4. RADIOACTIVITY

The radioactivity of the QUPIDs has been measured in the Gator screening facility, operated by the University of Zurich at LNGS. The facility consists of a high-purity, p-type coaxial germanium (HPGe) detector with a 2.2 kg sensitive mass, operated in an ultra-low background shield continuously flushed with boil-off nitrogen gas to suppress radon diffusion. With an integral background rate of 0.16 events/min in the 100-2700 keV region, Gator is one of the world's most sensitive Ge spec-

trometers [23]. In this work we present the results of the screening of two batches of five QUPIDs.

To determine the specific activities for the ^{238}U and ^{232}Th chains, as well as for ^{60}Co and ^{40}K , the most prominent γ -lines of the respective decays are analyzed using efficiencies as determined by a detailed Monte Carlo simulation of the detector, shield, and QUPID samples. The latest background run of Gator had been taken for a duration of two months prior to the QUPID screening. In the case in which no events were detected above the background, upper limits on the specific activities were calculated according to the method proposed in [24].

The radioactivities for each QUPID are < 17.3 for ^{238}U , 0.3 ± 0.1 for ^{232}Th , 0.4 ± 0.2 for ^{40}K and < 0.18 for ^{60}Co (all values in mBq). These results⁴ are reported in the first column of Table I.

To verify whether the background coming from the QUPIDs match the requirements of future detectors, a preliminary design of a ton-scale liquid xenon detector has been studied using the **Geant4** Monte Carlo software package [25]. The simulation considers (i) a liquid xenon TPC, with a diameter of 1 m and height of 1 m (corresponding to a total mass of 2.3 ton), (ii) two arrays of 121 QUPIDs each placed at the top and bottom of the TPC, (iii) all the main detector materials. To estimate the background level arising from the QUPIDs we have implemented the code assuming the radioactive contamination from the Gator data.

In the simulation we have considered the standard analysis cuts used by the XENON collaboration [4, 26], with a conservative assumption of 99% rejection power on the electromagnetic background. The study has been repeated for different fiducial volumes, that is, cutting the top, bottom and lateral face of the liquid xenon and considering only the inner cylindrical volume as target

⁴ Although ^{226}Ra belongs to the ^{238}U chain with a half-life of 1600 years, it bonds easily with other electronegative elements and can be absorbed in strong thermal and/or chemical processes, generating a break in the equilibrium of the chain. For this reason, the two parts of the chain (i.e. ^{238}U and ^{226}Ra) have been treated separately in the analysis.

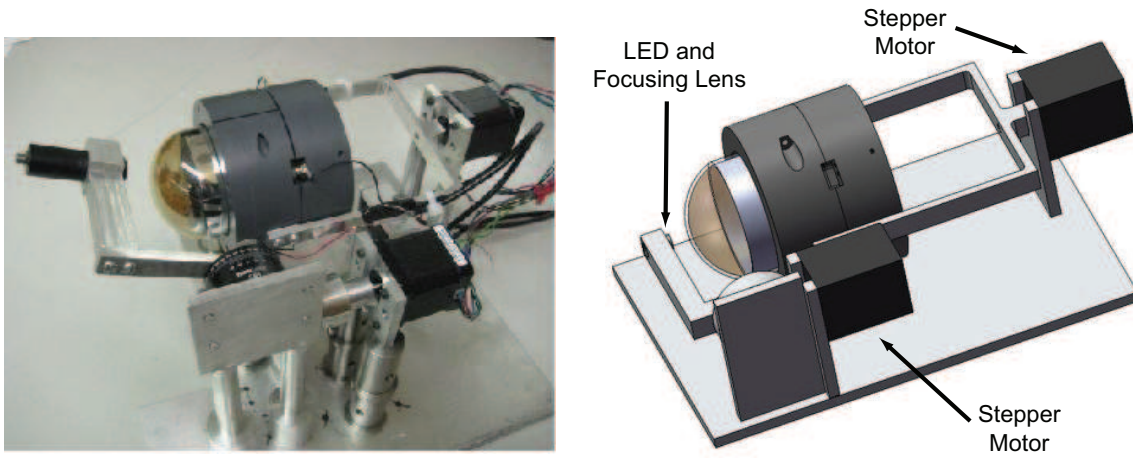


FIG. 2: On the *left*, photograph of the QUPID uniformity system. On the *right*, 3D rendering of the QUPID uniformity system. In this system, the QUPID is rotated along the ϕ axis, and the LED scans along the θ axis.

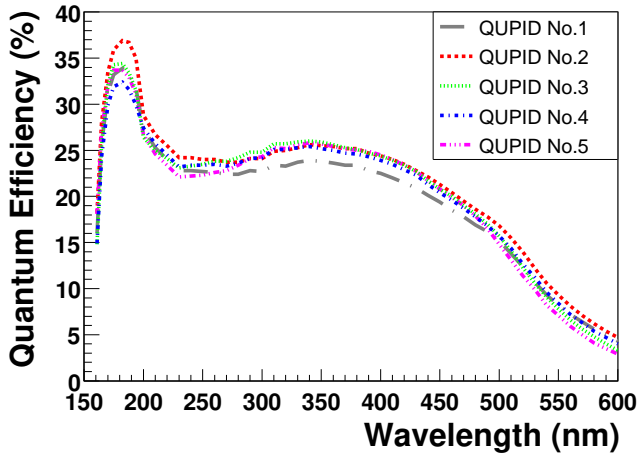


FIG. 3: Quantum efficiency measured for various QUPIDs, optimized for liquid xenon operation, with the maximum at 178 nm being $34 \pm 2\%$. The numbering of the QUPIDs are conventional and do not follow the production numbers.

material and region of interest for any energy deposit. In Table I the results of the Monte Carlo simulation for fiducial volume cuts of 0, 5, and 10 cm are presented, along with the results of the screening for each chain.

In a $1\text{ m} \times 1\text{ m}$ liquid xenon detector with 10 cm fiducial volume cuts (corresponding to a target mass of 1.1 ton) 242 QUPIDs would give a total background rate < 0.07 events/year, in the energy range between 2 and 18 keV. This result, unachievable using the standard PMTs, would perfectly satisfy the requirements of the next generation dark matter experiments [18, 19].

5. PHOTOCATHODE

A. Quantum Efficiency

The photocathode used in the QUPID has been specifically developed [27] by Hamamatsu Photonics to achieve the highest quantum efficiency (QE) for 178 nm photons, corresponding to the xenon scintillation light.

The QE has been measured at room temperature by comparing the response of the QUPID to a standard PMT, calibrated by means of a NIST standard UV sensitive photodiode [28]. Fig. 3 shows the QE measurements for different QUPIDs measured at Hamamatsu. All the tested QUPIDs show a maximum QE $> 30\%$ around 178 nm. The sharp cutoff at 170 nm is due to absorption by the quartz window.

A photocathode version optimized for operation in liquid argon is under development. The quartz window of the QUPID is opaque to argon scintillation light, and thus a wavelength shifting (WLS) material⁵ must be used to shift the scintillation light to ~ 400 nm. The photocathode used for liquid argon detectors will then have the highest QE around visible light.

B. Uniformity

The uniformity of the QUPID was measured at room temperature by focusing an LED onto the photocathode and scanning over the entire face. The LED is powered by a DC power supply and provides a spot of 1 mm focused on the spherical surface of the QUPID, while two stepper motors control independently:

⁵ A possible WLS material in consideration is Tetraphenyl Butadiene (TPB).

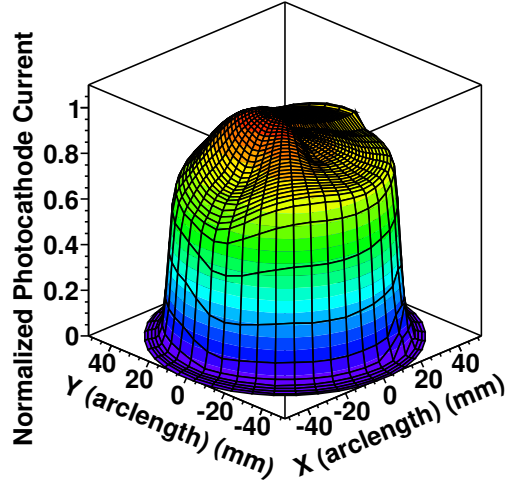
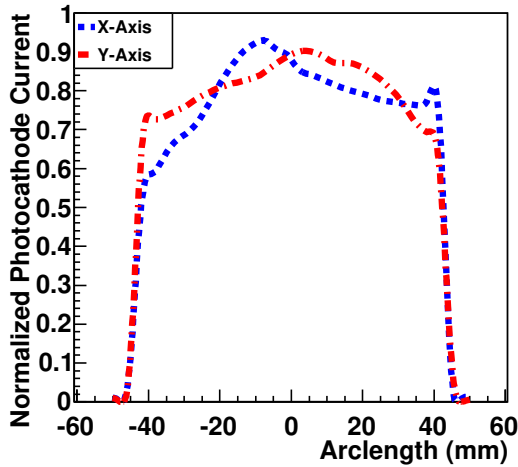


FIG. 4: Photocathode uniformity results for QUPID (No.7) showing X and Y slices (on the *left*), and a 3D plot (on the *right*). The QUPID is uniform to $\sim 80\%$ across the face.

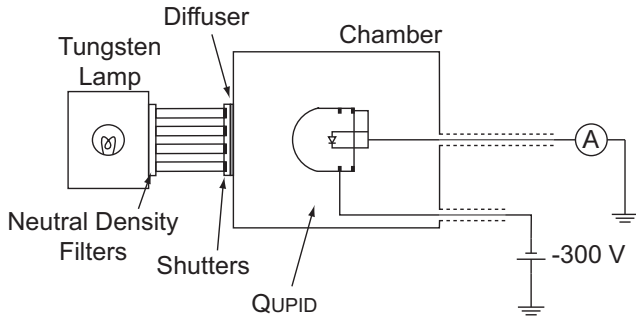


FIG. 5: Photocathode linearity system. A tungsten lamp, neutral density filter wheel, and diffuser, along with four shutters, control the illumination of the photocathode of the QUPID. The photocathode is supplied with -300 V while the APD and the grounding ring are read out by a picoammeter.

- (i) the location of an LED along the θ axis (i.e. moving from the top of the photocathode dome towards the indium rings, in steps of 1°);
- (ii) the position of the QUPID along the ϕ axis (i.e. moving the QUPID around its main rotation axis, in steps of 10°).

A photo and a drawing of the setup are shown on the left and right of Fig. 2 respectively.

The uniformity has been tested by measuring the current from the photocathode by means of a picoammeter while applying 150 V to the grounding ring and to both the anode and the cathode of the APD. The results are shown in Fig. 4. The photocathode is uniform to about 80% across the face.

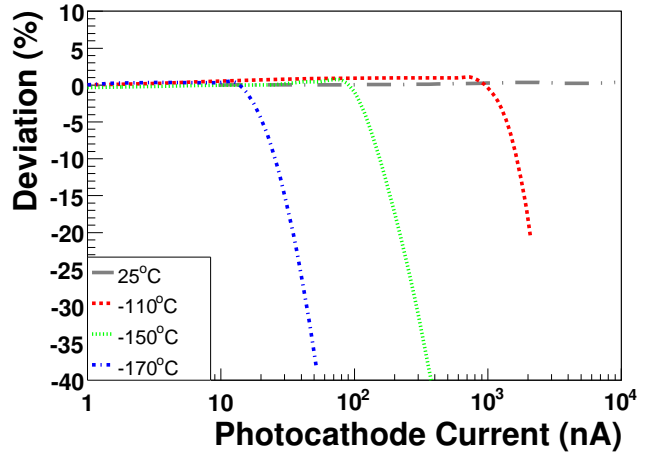


FIG. 6: Photocathode linearity versus current at various temperatures of QUPD (No.3). The photocathode deviates from linearity at lower currents for lower temperatures. At liquid xenon temperature, saturation occurs above $1 \mu\text{A}$.

C. Linearity

The Low Temperature Bialkali photocathode (Bialkali-LT) developed by Hamamatsu Photonics and employed in the QUPIDs is optimized for linearity over a wide dynamic range at low operating temperatures [27], where common photocathodes become nonlinear as the resistivity increases.

For neutrinoless double beta decay in ^{136}Xe , the expected energy deposited is 2.458 MeV and the largest signals come from the S2s. While S1 signals have a light yield of 3 photoelectrons/keV (pe/keV), corresponding to

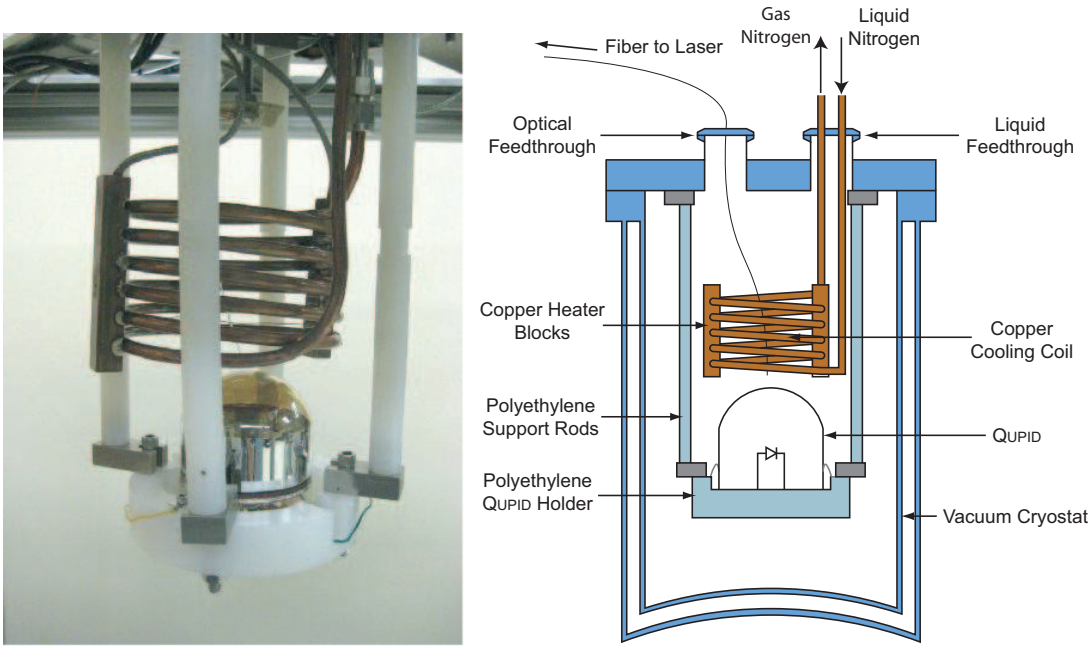


FIG. 7: On the *left*, photograph of the liquid nitrogen cooling system and the QUPID support. On the *right*, diagram of the nitrogen cooling system and the QUPID support.

about 7,400 photoelectrons, the S2 signals have 200 times the number of photoelectrons spread out over $2 \mu\text{s}$. This results in a maximum photocathode current of about 12 nA. The photocathode response must then be linear up to at least this current.

To test the linearity, the QUPID was uniformly illuminated by a tungsten lamp coupled with a diffuser. A set of four shutters and a neutral density filter wheel were used to vary the light intensity. The photocathode has been supplied with a potential of -300 V and the APD (both the anode and the cathode) and the grounding ring were connected to a picoammeter. Fig. 5 shows a diagram of the testing system used for the photocathode linearity.

Each of the shutters has been opened individually while keeping all the others closed, and the corresponding photocathode current was read out with the picoammeter (I_i , where $i = 1, 2, 3, 4$). The current with all the shutters opened has been measured (I_{all}) as well. The same procedure was repeated with different filters, spanning different light intensities, thereby increasing/decreasing the photocathode current in response to the changing light intensity. In such a configuration, the deviation from linearity can be defined as

$$\Delta Lin = \frac{I_{tot} - \sum_{i=1}^4 I_i}{\sum_{i=1}^4 I_i}, \quad (1)$$

which in the ideal case of perfect linearity must be equal to zero for all the filter configurations (as the sum of all photocathode currents with only one shutter open should be equal to the current with all the shutters open).

Fig. 6 shows ΔLin versus the photocathode current for different temperatures. At -110°C the linearity is well maintained up to $1 \mu\text{A}$. This value largely overcomes the

12 nA dynamic range required for neutrinoless double beta decay detection in liquid xenon.

6. ANODE

A. Leakage Current and Gain Measurements

As the main use of the QUPID will be in noble liquids, great care has been taken to test its performance at cryogenic temperatures. In Fig. 7 a picture and a drawing of the cryogenic system is shown.

After positioning the QUPID in the cryostat, a vacuum is pumped using an oil free pumping station⁶ and dry nitrogen gas is introduced. Liquid nitrogen is then flowed through a copper coil at a constant rate to cool the surrounding nitrogen gas, cooling the QUPID. Two 100 W resistive heaters inserted into copper bars (soldered onto the copper coil) serve as temperature stabilizers, controlled by a Proportional-Integral-Derivative (PID) controller⁷ and monitored by Resistance Temperature Detectors (RTDs). At -100°C the temperature can be maintained within an accuracy of 0.1°C .

Within the cryostat, the QUPID is held in a polyethylene support structure suspended from the top flange of the cryostat by four polyethylene rods. A set of four stainless steel clips hold the QUPID to the polyethylene

⁶ The station (Pfeiffer Vacuum Hi-Cube Eco-3 Pumping Station) consists of a diaphragm pump and a turbomolecular pump.

⁷ Omega Model CN8201 Temperature Controller

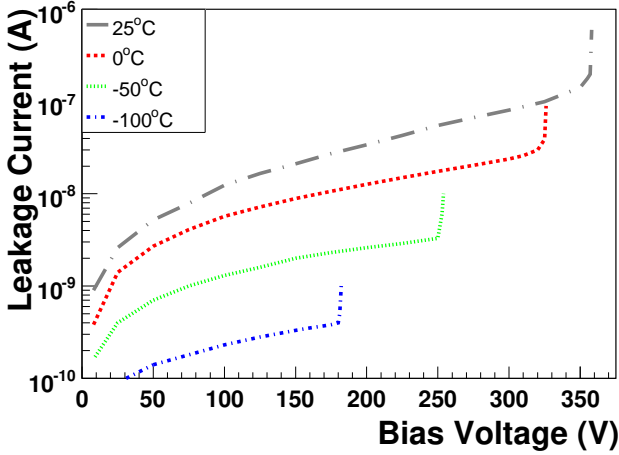


FIG. 8: Leakage current versus the APD bias voltage at various temperatures of QUPID (No.6). As the temperature decreases, the overall leakage current decreases. Also, the breakdown voltage, recognizable from the dramatic increase of the slope of the leakage current curves, decreases with the temperature. At liquid xenon temperature, the leakage current is < 1 nA while breakdown occurs at 180 V.

lene, which also provide connections for the photocathode voltage and the grounding ring. High voltage and coaxial feedthroughs are used to provide the photocathode voltage, bias voltage and readout. An optical fiber feedthrough is placed on the cryostat, and a fiber is pointed towards the QUPID. All of the readout electronics are placed outside the cryostat.

In APDs, the leakage current increases approximately linearly with the bias voltage until breakdown, above which the leakage current increases drastically. To measure the leakage current and breakdown voltage at low temperature, the QUPID was placed in the cryostat, tightly insulated from external light, with both the photocathode and grounding ring grounded. A negative voltage⁸ was applied to the APD anode while the cathode was connected to a picoammeter.⁹ Fig. 8 shows the leakage current curves for different temperatures as a function of the applied bias voltage. As expected, the leakage current follows a linear increase up to a breakdown voltage, where it rises dramatically. At liquid xenon temperature, the leakage current is about 1 nA. Fig. 9 shows the temperature dependence of the breakdown voltage for various QUPIDs. At -100°C the breakdown voltage is about 180 V. The total gain of the QUPID includes the bombardment gain, given by the photoelectrons impinging onto the APD, and the avalanche gain, given by the avalanche process inside the APD.

To measure the gain we have used a pulsed laser light of 405 nm wavelength and 70 ± 30 ps pulse width emitted

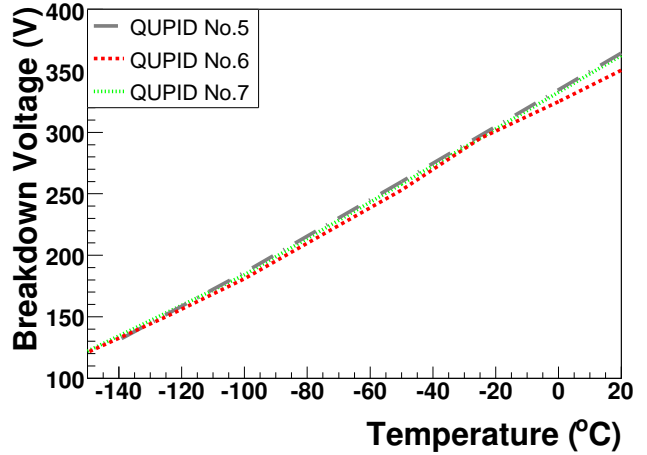


FIG. 9: Temperature dependence of the breakdown voltage for different QUPIDs. The breakdown voltage shows a linear trend as the temperature varies.

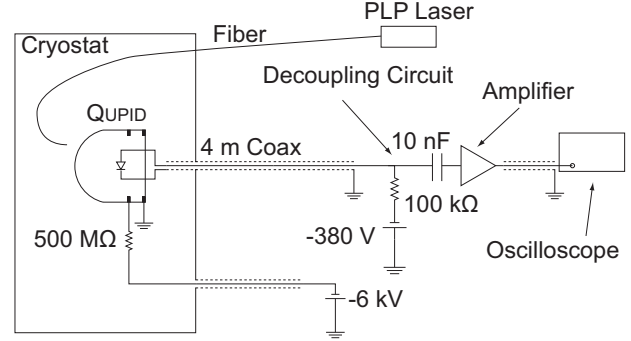


FIG. 10: Testing setup with the pulsed laser light used for gain and anode linearity measurement. The photocathode is supplied with high voltage and a bias voltage is connected to the APD anode through a decoupling circuit. The output of the APD is passed through an amplifier to the readout system, an oscilloscope in this case.

with 100 kHz repetition.¹⁰ The photocathode voltage¹¹ was set to -6 kV and the APD bias voltage just below the breakdown. In order to minimize the cabling passing through the cryostat, both the signal and the bias voltage were carried by the same coaxial cable. To read out the signal, a decoupling circuit was placed outside of the cryostat, along with an amplifier¹² and an oscilloscope for data acquisition.¹³ Fig. 10 shows the schematic of

⁸ Stanford Research Systems Model PS350 +/- 5 kV Power Supply.

⁹ Keithley Model 486 Picoammeter.

¹⁰ Hamamatsu Model C10196 Laser Controller with Model M10306-30 PLP-10 Laser Head.

¹¹ Stanford Research Systems Model PS355 -10 kV Power Supply

¹² RFBay Model LNA-1440 Amplifier, 40 dB gain, 1.4 GHz bandwidth

¹³ LeCroy WaveRunner 204MXi-L Oscilloscope, 10 GS/s, 2 GHz bandwidth

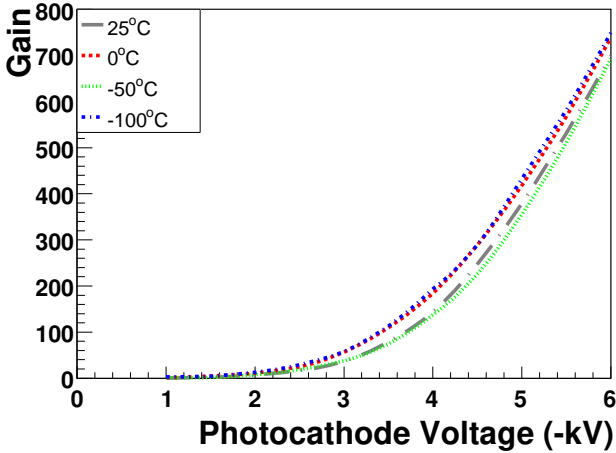


FIG. 11: Bombardment gain of QUPID (No.6) for various temperatures. The bombardment gain shows no temperature dependence and reaches a maximum of 750.

the readout used for the gain measurements.

To measure the bombardment gain of the QUPID, we integrated the signals read out on the oscilloscope for different photocathode voltages, up to -6 kV. Then we proceeded as follows:

- (i) the gain values obtained are in arbitrary units and must be decoupled from the avalanche gain;
- (ii) at large voltages (where the curve shows a linear trend) for each 3.6 eV from the impinging photoelectron, one electron-hole pair is created in the APD [29];
- (iii) the gain curve is then scaled in order to set an increase of one unit in the gain for every 3.6 V.

The outcome of this procedure is shown in Fig. 11, where the bombardment gain versus the photocathode voltage is reported for different temperatures. The nonlinear trend at negative voltages smaller than -4 kV is due to a dead layer of the APD, which stops the photoelectrons that do not have enough energy to penetrate into the active area of the APD. At -6 kV, the QUPID achieves a bombardment gain of above 700, independent of the temperature.

The avalanche gain is measured in a similar fashion, but instead scanning the APD bias voltage just below the breakdown value, keeping the photocathode voltage at -6 kV. To obtain the absolute normalization we:

- (i) determine the total gain from a single photoelectron spectrum;
- (ii) divide this value by the previously obtained bombardment gain, thereby extracting the avalanche gain;
- (iii) scale the gain versus bias voltage curve to make it match with the value obtained in (ii) for that specific bias voltage.

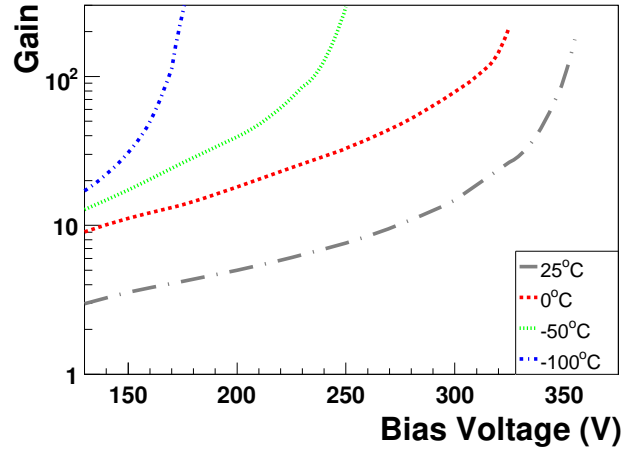


FIG. 12: Avalanche gain of QUPID (No.6) for various temperatures. As the temperature decreases, the avalanche gain increases for a set bias voltage. A maximum avalanche gain of 300 is seen at -100° C.

In Fig. 12 the avalanche gain value versus the bias voltage is reported. A strong temperature dependence of the avalanche gain can be seen, with the gain increasing as the temperature decreases.

The total gain of the QUPID is then $700 \times 200 \sim 10^5$, enough for single photoelectron detection.

B. Linearity

As discussed in Sec. 5 C, the photocathode must be linear up to at least 12 nA. The anode must then be linear up to this value times the gain of the QUPID. For a gain of 10^5 , the QUPID anode should be linear to 1.2 mA.

The QUPID anode linearity system consists of two rotating neutral density filter wheels controlled by two stepper motors. One is made of a continuously variable filter wheel with a range of optical densities from 0 to 2.0, the other is a set of discrete filters with optical densities ranging from 0 to 5.0.¹⁴ An ultrabright LED¹⁵ provides pulsed light which is attenuated through the filters and is brought to the QUPID through an optical fiber. Fig. 13 shows a photograph and a diagram of the testing setup.

For the measurement, the LED is pulsed at alternating light levels with a fixed brightness ratio of 1:4, resulting in alternating high and low currents from the APD. Each pulse has a width of 1 μ s, and the dim and bright pulses alternate at a frequency of 600 Hz. The light from the LED is then attenuated through the two filter wheels. In this way, while the overall brightness is changed using

¹⁴ The optical density A is defined as $A = \log_{10}(I_o/I)$, where I_o and I are the intensity of the incoming and outgoing lights respectively.

¹⁵ Nichia Model NS6B083T 470 nm LED

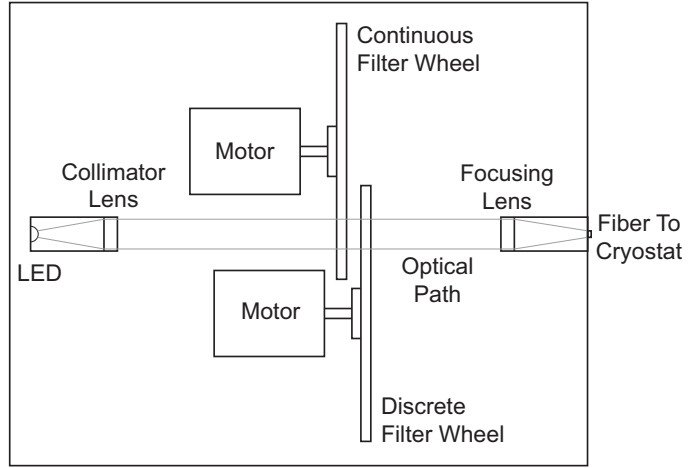
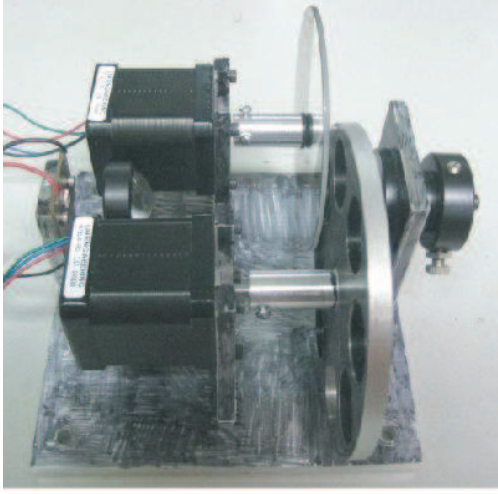


FIG. 13: On the *left*, a photograph of the anode linearity pulsing system. On the *right*, a diagram of the anode linearity pulsing system. A pulsed LED shines through two sets of filters and is passed into a fiber, which then carries the light to the QUPID.

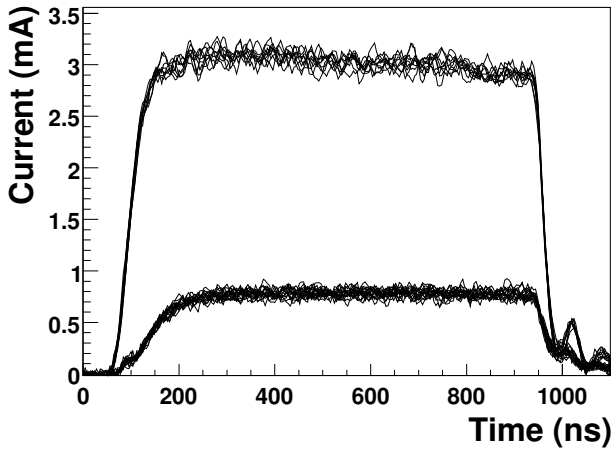


FIG. 14: Waveforms from QUPID (No.5) at the bright and dim light levels from the LED of the linearity testing system. The waveforms from the bright pulses are at 3 mA, where the QUPID starts showing a deviation from linearity at the 5% level.

different combinations of the filters, the 1:4 brightness ratio is maintained. The waveforms are then read out with an oscilloscope and integrated.

At low light levels for both dim and bright pulses, the anode current of the QUPID shows the same constant ratio of 1:4. As the light level increases (by decreasing the optical density of the filter wheels) the absolute value of the anode current increases, and the ratio of low and high anode current starts to deviate from the original 1:4, thereby showing nonlinear behavior. Fig. 14 shows the output current from the QUPID for the bright and dim light pulses while Fig. 15 shows the measured anode linearity.

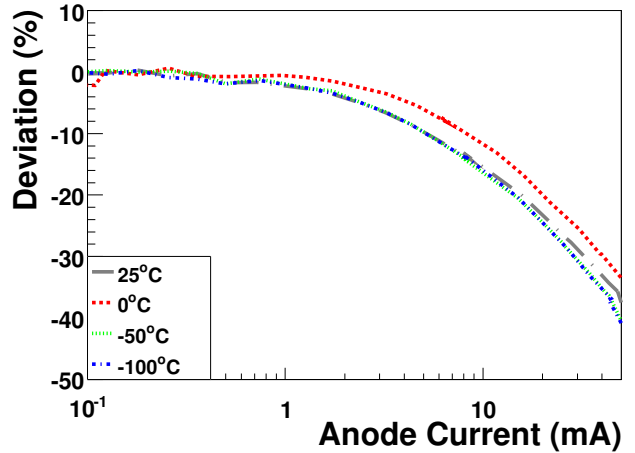


FIG. 15: Anode linearity for various temperatures of QUPID (No.5). A 5% nonlinear behavior starting at an anode current of 3 mA is evident. No temperature dependence is observed.

Although nonlinear behavior begins to appear at the 5% level from 3 mA peak anode current with a gain of 10^5 , the nonlinearity of the QUPID can be characterized and corrected for high light levels, thereby increasing the effective dynamic range.

Tests at -100°C in the cryogenic setup described above prove that the linearity of the QUPID is independent of the temperature.

C. Collection Efficiency

The same scanner for testing the photocathode uniformity (see Sec. 5 B and Fig. 2) has also been used for

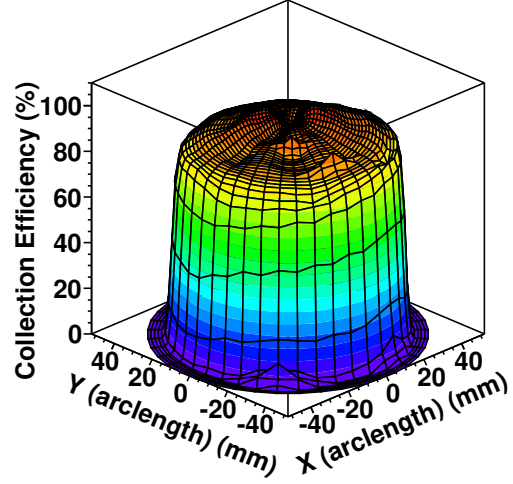
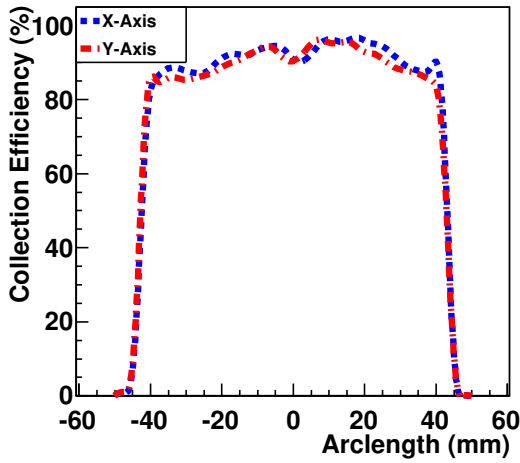


FIG. 16: Photoelectron collection efficiency in X and Y slices (on the *left*), and in a 3D plot (on the *right*) for QUPID (No.7). The collection efficiency is $> 80\%$ across the entire face of the QUPID.

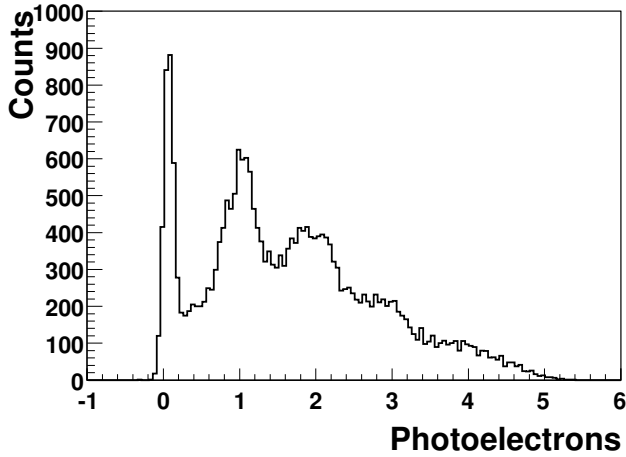


FIG. 17: Charge distribution measured for dim laser pulses on QUPID (No.5). Peaks of 0, 1, 2, and 3 photoelectrons can be clearly seen.

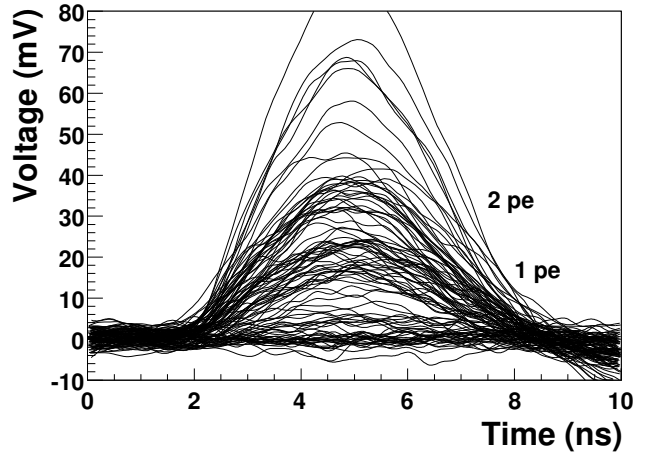


FIG. 18: Waveforms for dim laser pulses at -100° C from QUPID (No.5). A 4 m coaxial cable was used between the cryostat and the decoupling circuit. Even with this long cable, clear bands corresponding to 0, 1, and 2 photoelectrons are well visible. The rise time and fall time were measured at 1.8 ± 0.1 ns and 2.5 ± 0.2 ns respectively, with a pulse width of 4.20 ± 0.05 ns. The transit time spread was measured at 160 ± 30 ps.

the anode uniformity. In these measurements, the photocathode was held at -6 kV while a bias voltage of -250 V was applied to the anode of the APD. The current was read through the cathode of the APD using a picoammeter. The photoelectron collection efficiency can be inferred from the ratio between anode uniformity and photocathode uniformity scaled by the total gain. Fig. 16 shows the photoelectron collection efficiency to be over 80% for a majority of the surface.

7. WAVEFORMS AND TIMING

In conjunction with the gain measurements, waveforms of the QUPID were also obtained at low light levels. With the QUPID in the same setup for gain measurements, the intensity of the picosecond laser was lowered such that only a small number of photoelectrons were observed. The picosecond laser controller provided a trigger output

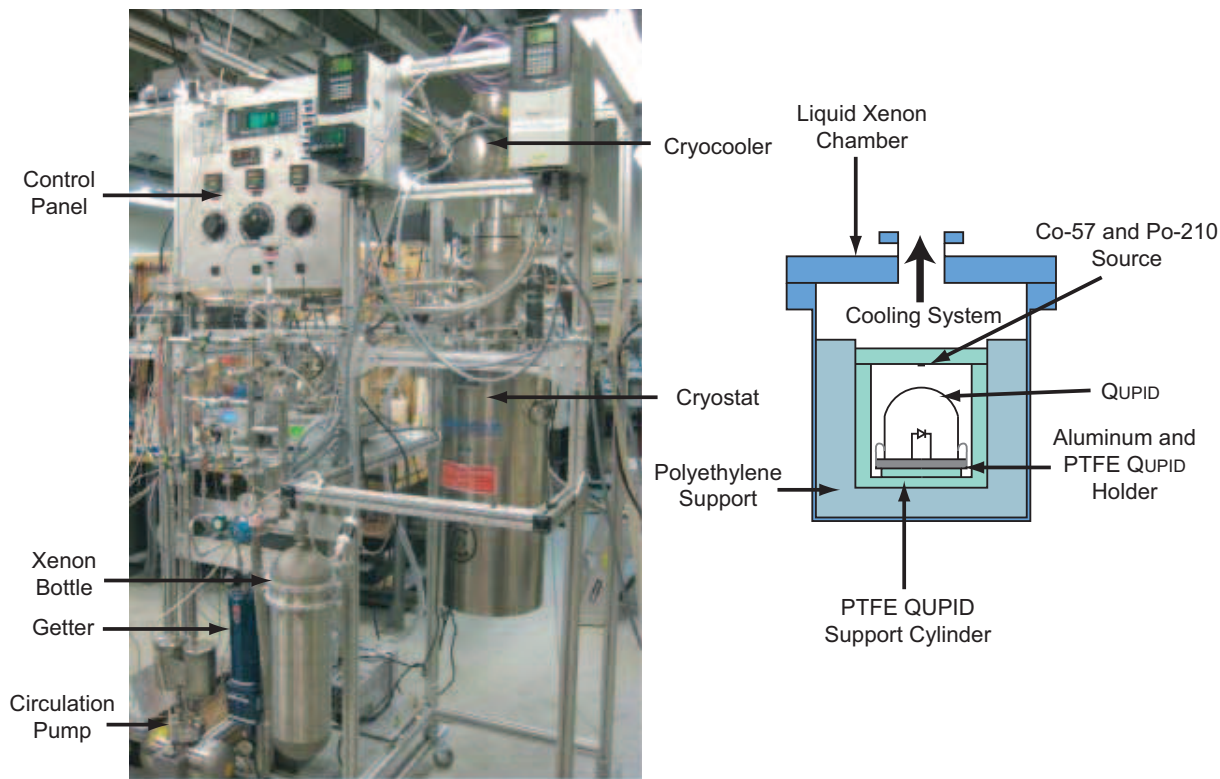


FIG. 19: On the *left*, photograph of the liquid xenon test system. On the *right*, drawing of the liquid xenon cell inside the cryostat. The QUPID is held in a polyethylene, PTFE, and aluminum holder in liquid xenon, and two radioactive sources are placed inside to generate scintillation light.

synchronized to the laser pulse. A very narrow window was then chosen around this point for integration of the signal, and the resulting charge of the signals were plotted in a histogram. Fig. 17 shows the charge distribution of QUPID signals from 0, 1, 2, and 3 photoelectrons. A narrow pedestal of zero photoelectrons can be seen in the histogram, and clear peaks corresponding to integer number of photoelectrons are apparent.

As ton-scale dark matter detectors will require long cabling of the order of several meters, to ensure that the readout electronics are far from the target volume, we included a 4 m coaxial cable between the cryostat and the decoupling circuit. Fig. 18 shows 100 waveforms registered at -100°C . Even with such a long cable before amplifying the signal, there is little degradation of the waveform, and bands of 0, 1, and 2 photoelectrons can be clearly seen.

Timing information of the waveforms was measured in the same setup. Defining the rise (fall) time as the time for the pulse to go from 10% to 90% of the pulse height (and vice-versa), we obtained a rise time of $1.8 \pm 0.1\text{ ns}$ and a fall time of $2.5 \pm 0.2\text{ ns}$. The pulse width, defined as the full width at half maximum (FWHM) of the waveforms, is $4.20 \pm 0.05\text{ ns}$. The transit time spread of the QUPID has been measured by comparing the time difference between the laser trigger and the peak of the waveform. Histogramming this time difference and determining the FWHM, we obtained $160 \pm 30\text{ ps}$. It is

important to note that this value can be considered as an upper limit as it includes the uncertainties arising from the jitter of the laser trigger.

8. QUPID IN LIQUID XENON

The QUPID has been tested extensively in a liquid xenon setup built at UCLA, which is shown in Fig. 19. The QUPID was placed inside a PTFE and aluminum housing supported by a polyethylene structure inside a stainless steel chamber. The chamber was then placed inside a vacuum cryostat. A cryocooler¹⁶ was used to liquefy the xenon and to maintain liquid xenon temperature during operation. The PTFE housing was fully immersed in the liquid xenon allowing for the QUPID to operate in single-phase mode. The temperature and pressure were held constant at -100°C and 1.6 bar, and the system was operated under stable conditions for approximately two weeks. During this period, the xenon gas was purified with a hot metal getter¹⁷ in a closed recirculation loop¹⁸.

¹⁶ Q-Drive Model 2S132K-WR Cryocooler

¹⁷ SAES Model PS3MT3R1 Mono-torr Getter

¹⁸ Q-Drive/UCLA Model 2S132K-UCLA Pump

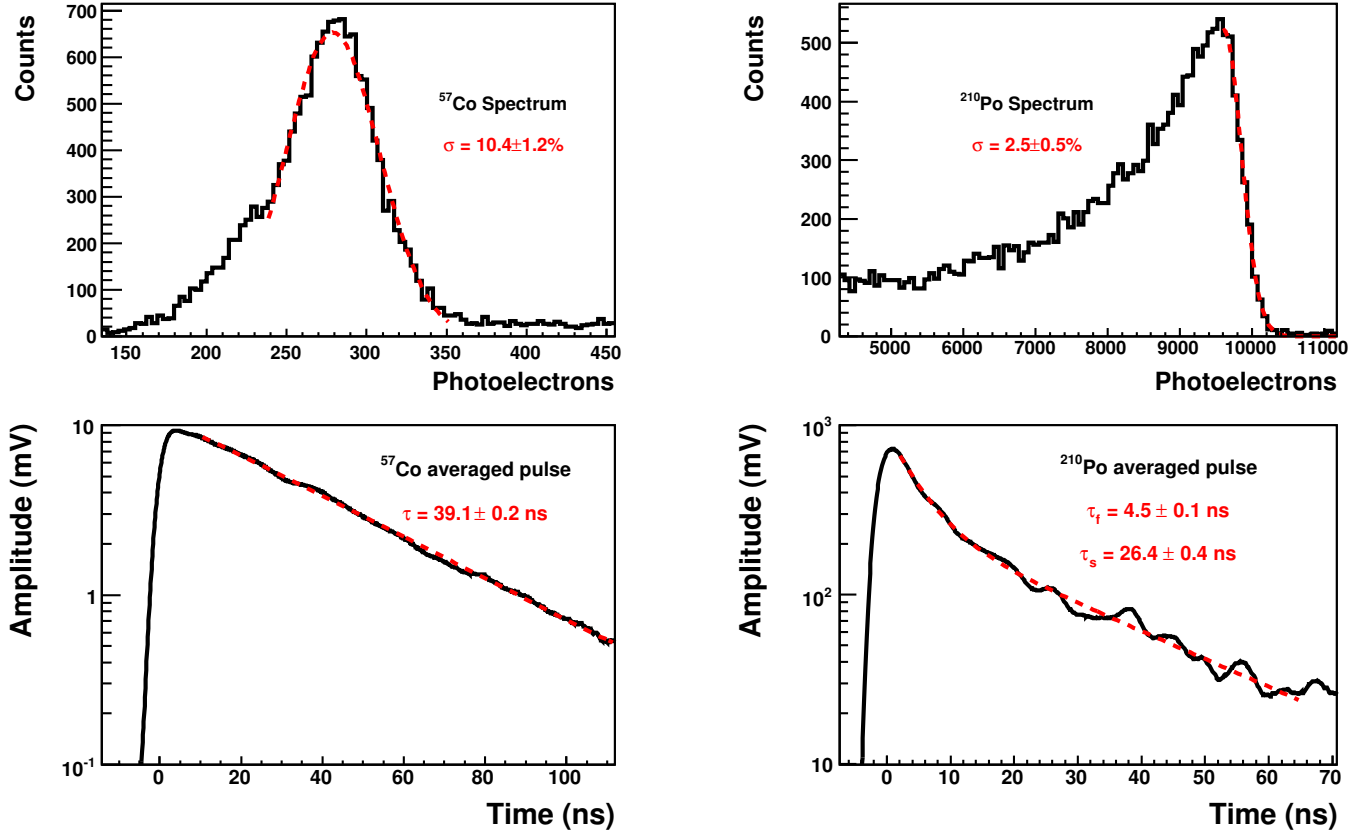


FIG. 20: Clockwise from top left: ^{57}Co energy spectrum, ^{210}Po energy spectrum, ^{210}Po averaged waveform, ^{57}Co averaged waveform using QUPID (No.7). The average light yield from several data sets of ^{57}Co is 2.0 ± 0.2 photoelectrons/keV (pe/keV) with a resolution of $10.4 \pm 1.2\%$. The average light yield obtained from the ^{210}Po source was 1.6 ± 0.2 pe/keV with a resolution of $2.5 \pm 0.5\%$. The average waveforms also show exponential fits in red. A decay time of 39.1 ± 0.2 ns is found from the ^{57}Co pulses, and a fast and slow decay time of 4.5 ± 0.1 ns and 26.4 ± 0.4 ns are seen in the ^{210}Po waveforms.

Source	Type	Energy	Light Yield	Resolution	Decay Time	Previously Measured Decay Time [30, 31]
^{57}Co	γ	122 keV, 86% 136 keV, 11%	2.0 ± 0.2 pe/keV	$10.4 \pm 1.2\%$	39.1 ± 0.2 ns	34 ± 2 ns
^{210}Po	α	5.3 MeV	1.6 ± 0.2 pe/keV	$2.5 \pm 0.5\%$	4.5 ± 0.1 ns, fast (71%) 26.4 ± 0.4 ns, slow (29%)	4.3 ± 0.6 ns, fast (69%) 22.0 ± 2.0 ns, slow (31%)

TABLE II: Parameters for the sources observed in liquid xenon, including light yield, resolution, and decay times. This particular QUPID had a lower quantum efficiency of 20% at 178 nm.

Gain calibration of the QUPID was performed by measuring its response to light from the picosecond laser, fed into the PTFE housing via an optical fiber. The read-out setup was the same as for the gain measurements (Fig. 10), however no amplifier was used. Internal ^{57}Co and ^{210}Po sources, placed just above the QUPID, were used to measure and monitor the QUPID response to the scintillation light of xenon. The presence of impurities, out-gassing of the surrounding material, and a PTFE housing that was not fully optimized limited the achievable light detection efficiency, which was found to be strongly dependent on the recirculation speed through-

out the run. Fig. 20 shows the response of the QUPID to the ^{57}Co and ^{210}Po sources, including pulse shapes and energy spectra.

Table II summarizes the parameters measured from each of the sources. ^{57}Co decays through the emission of a 122 keV γ -ray with an 86% branching ratio, and a 136 keV γ -ray with 11% branching ratio. As seen in Fig. 20, these two lines are not separated but give a single peak whose weighted average energy of 123.6 keV was used for further calculations. The ^{57}Co light yield averaged over a few hours was found to be 2.0 ± 0.2 pe/keV, with $10.4 \pm 1.2\%$ energy resolution. The stated errors are es-

QUPID Parameters		
Dimensions	Outer Diameter	71 mm
	Effective Photocathode Diameter	64 mm
	Radius of Hemispherical Photocathode	37 mm
	Total Height	76 mm
Radioactivity	^{238}U	$< 17.3 \text{ mBq}$
	^{226}Ra	$0.3 \pm 0.1 \text{ mBq}$
	^{232}Th	$0.4 \pm 0.2 \text{ mBq}$
	^{40}K	$5.5 \pm 0.6 \text{ mBq}$
	^{60}Co	$< 0.18 \text{ mBq}$
Performance		25° C -100° C
Photocathode	Material	Bialkali-LT
	Quantum Efficiency at 178 nm	$34 \pm 2\%$ $-$
	Linearity ^a	$> 10 \mu\text{A}$ $> 1 \mu\text{A}$
Electron Bombardment	Acceleration Voltage	6 kV
	Typical Gain	750
	Maximum Gain	800
APD	Diameter	3 mm
	Capacitance	11 pF
	Leakage Current	200 nA 0.3 nA
	Breakdown Voltage	360 V 180 V
	Typical Gain	200
	Maximum Gain	300
Anode Output	Typical Total Gain	1.5×10^5
	Maximum Total Gain	2.4×10^5
	Linearity ^a	3 mA
Timing Properties	Rise Time (10%-90%)	$1.8 \pm 0.1 \text{ ns}$
	Fall Time (90%-10%)	$2.5 \pm 0.2 \text{ ns}$
	Pulse Width (50%-50%)	$4.20 \pm 0.05 \text{ ns}$
	Transit Time Spread (FWHM)	$160 \pm 30 \text{ ps}$

^aMaximum current within 5% nonlinearity

TABLE III: Summary of the key parameters of the QUPID.

timated from the fluctuations of the light yield for the measurements taken with different trigger threshold values over the span of a few hours.

Fig. 20 also shows the part of the measured spectrum dominated by the peak due to the ^{210}Po source. ^{210}Po decays by a 5.3 MeV α -particle, and from this a light yield of $1.6 \pm 0.2 \text{ pe/keV}$ was obtained with a resolution of $2.5 \pm 0.5\%$. These measurements were taken on a different date than the ^{57}Co data, and thus the conditions, such as xenon purity, changed between the data sets.

The scintillation light from liquid xenon has two decay components due to the de-excitation of the singlet and triplet states of the excited dimer Xe_2^* [32]. The averaged pulse shape for ^{210}Po α -particle and ^{57}Co γ -ray interactions, together with the fit of their overall decay profiles, are shown in Fig. 20 (bottom). The α -particle interactions from ^{210}Po had measured fast and slow decay times of $4.5 \pm 0.1 \text{ ns}$ and $26.4 \pm 0.4 \text{ ns}$ respectively, with an intensity ratio of the fast to slow components being 71% fast and 29% slow. The ^{57}Co pulses had a single decay time of $39.1 \pm 0.2 \text{ ns}$. These decay time constants are similar to the previously published values of $4.3 \pm 0.6 \text{ ns}$ and $22.0 \pm 2.0 \text{ ns}$ for the α -particle fast and slow com-

ponents, with a ratio of 69% fast and 31% slow, and to $34 \pm 2 \text{ ns}$ for γ -interactions [30, 31].

9. CONCLUSION

The QUPIDS, the new low radioactivity photodetectors developed and evaluated jointly by Hamamatsu Photonics and UCLA, show optimum characteristics for use in the next generation of dark matter and double beta decay detectors. In this work we have described the test setups and performance of seven QUPIDS. Table III shows a summary of the most relevant results.

QUPIDS have much lower radioactivity than conventional PMTs as measured at the Gator screening facility. Simulations of ton scale detectors including QUPIDS show that they satisfy the low background level required. The quantum efficiency, higher than 30% at the xenon scintillation wavelength, is competitive with standard photodetectors. A total gain of 10^5 , and the capability of single photon counting, fit very well with the detection of low intensity signals coming from WIMP-nuclei interactions. A wide linear dynamic range, up to 3 mA of anode cur-

rent at liquid xenon temperature, allows the QUPID to cover an energy range large enough for neutrinoless double beta decay detection. We have measured the QUPID uniformity to be above 80% over the entire surface, and have measured a good timing response of 1.8 ± 0.1 ns rise time, 2.5 ± 0.2 ns fall time, 4.20 ± 0.05 ns pulse width, and 160 ± 30 ps transit time spread. In a liquid xenon environment, we have demonstrated the QUPID's capability to detect scintillation light from γ -ray and α -particle interactions.

These characteristics make the QUPID an ideal replacement for PMTs in future experiments, such as DARKSIDE50, XENON1Ton, MAX, DARWIN, and XAX [10, 18, 19, 33, 34], and will represent a major contribution for the next generation of ton scale dark matter and double beta decay detectors.

10. ACKNOWLEDGEMENTS

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ing line and actual manufacturing. We would also like to thank Y. Ishikawa and K. Yamamoto from the Solid State division of Hamamatsu Photonics for the development of a new APD specifically optimized for the QUPID. Special thanks to D. Dreisbach, P. Hemphill, M. Levi, C. Reilly, J. Rolla, and T. White for their invaluable help in the development of the QUPID test systems, data taking and analysis, and H. Lockhart and the UCLA Machine Shop for the machining of many of the parts used in the test setups. We are indebted to E. Aprile, F. Calaprice, C. Galbiati, B. Sadoulet, and M. Tripathi for useful discussions. We also express our deep gratitude to the XENON collaboration for helpful advice and encouragement. This work was supported in part by US DOE grant DE-FG02-91ER40662, and by NSF grants PHY-0653459, PHY-0810283, PHY-0919363, and PHY-0904224, and we gratefully thank H. Nicholson and M. Salamon from the DOE, and J. Whitmore, J. Kotcher, and D. Lissauer from the NSF. Additional support was provided by the INPAC Fund from the UC Office of the President, the UCLA Dean, and UCLA Physics Chair funds, and we are thankful to R. Peccei, J. Rudnick, and F. Coroniti for financial support and encouragement. The work done at the Gator facility was supported by the Swiss National Foundation, Grant No. 20-118119 and No. 20-126993.

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